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The Neutron Spectra and the Resulting Fluence-kerma Conversions for ^{241}Am-Li(α, n) and ^{210}Po-Li(α, n) Sources

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A RADIOACTIVE Li(α, n) neutron source is unique because its spectrum with an average energy of about 0.5 MeV bridges the energy gap between photoneutron sources and the commonly used Be(α, n) sources. Radioactive neutron sources find wide application for the calibration of instruments and for this purpose an accurate knowledge of the neutron spectrum emitted is nearly always essential. Little is known about Li(α, n) source spectra[1,2] because few practical neutron spectrometers exist for the energy region in question. It appeared evident that the best way of obtaining the spectrum was by calculation, using the differential ^{7}Li(α, n)^{10}B cross sections which so far however were not known for the energy range of interest and had to be determined first.

The 4 MeV Van de Graaff accelerator of this laboratory which, by the use of a stripper arrangement, is capable of accelerating He^{++} ions to 7.6 MeV, was used as the source of α-particles. The kinematics of the reaction is as follows:

^{7}Li(α, n)^{10}B (ground state)

$$Q = -2.79 \text{ MeV } E_{th} = 4.38 \text{ MeV}$$

^{7}Li(α, n)^{10}B (first excited state)

$$Q = -3.51 \text{ MeV } E_{th} = 5.51 \text{ MeV}$$

The α-particle energy is 5.48 MeV from ^{241}Am and 5.30 MeV from ^{210}Po. Since the threshold for the first excited state, $E_{th} = 5.51$ MeV, is not yet reached only neutrons to the ground state of ^{10}B occur. Consequently the differential cross sections can simply be determined with a flat response neutron detector. A "Precision Long Counter"[3] was used and it was assumed that its response was constant[4] within the energy region of interest.

Figure 1 presents the results of the angular distribution measurements on a thin Li target after conversion to the center-of-mass system. The differential cross sections, $\sigma(\theta)$, have been normalized to the neutron production cross section as measured by MACKLIN and GIBBONS.[5,6] The errors for our measurements become rather pronounced at the back angles and at low α-energies; this is caused by large background corrections from neutron scattering within the target assembly. The curves drawn in Fig. 1 were obtained by a least-squares fit with Legendre polynominals up to the second degree. At

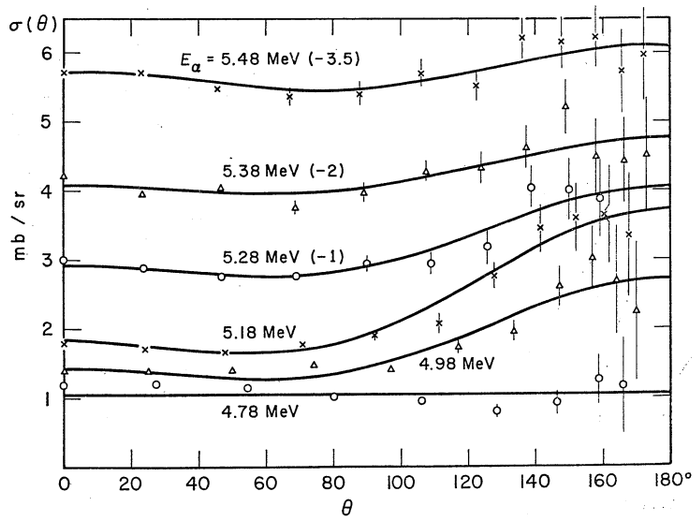

FIG. 1. The differential cross sections in the center-of-mass system. Experimental points were taken in 15 degs steps in the laboratory system. The three upper curves have been displaced. The bracketed values are to be subtracted from the cross section readings in the figure to obtain the actual value.

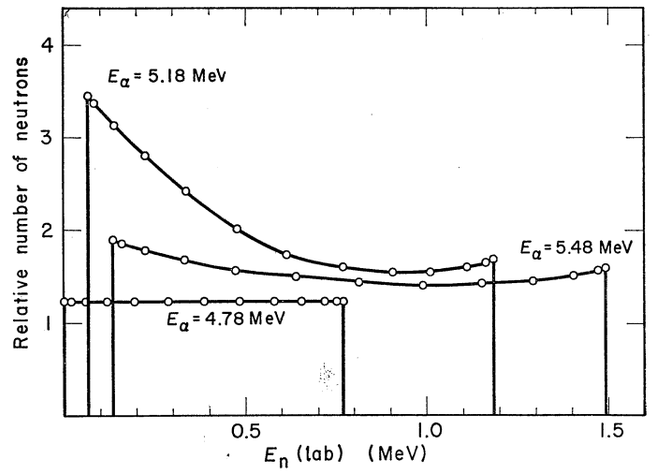

FIG. 2. Three of the distributions in Fig. 1 drawn as functions of the laboratory neutron energy E_n. These are the neutron spectra produced by monoenergetic α-particles. The circles indicate 15 deg steps in the c.m. system, starting with $\theta = 180$ deg at minimum neutron energy.

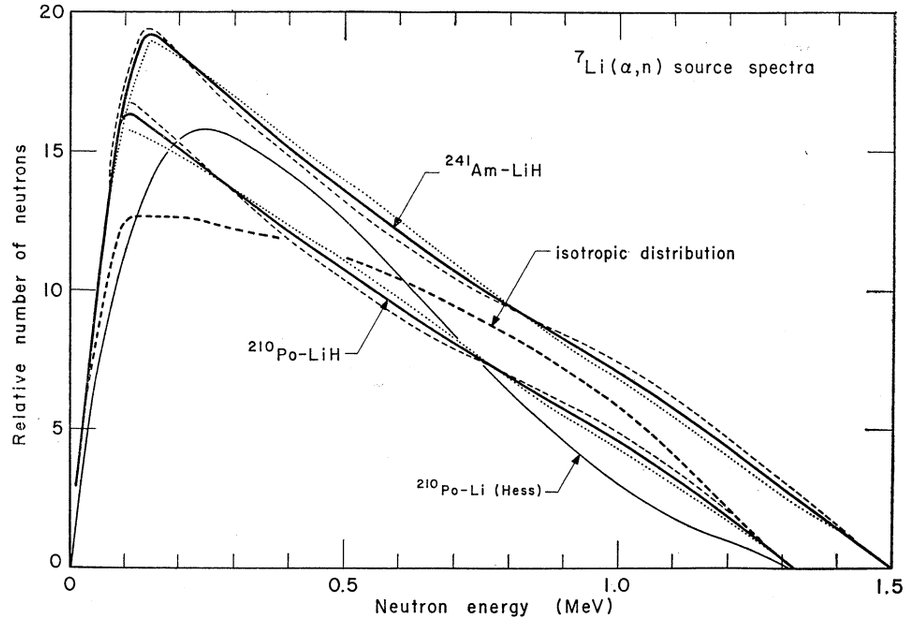

FIG. 3. Neutron spectra from Li(α, n) sources. To illustrate the effect of the non-isotropic angular distribution, the dashed curve, calculated for an isotropic distribution, is included. The spectrum calculated by HESS[2] is shown for comparison.

the lowest α-energy used, the c.m. distribution is compatible with an isotropic distribution. The energy of the emitted neutrons becomes double valued below 4.65 MeV which precludes angular distribution measurements by the present method. For the source spectra calculations, an isotropic distribution was assumed from $E_\alpha = 4.78$ MeV down to threshold. Such a trend would be expected from theoretical considerations. In any case, the effect on the source spectra is small because of the low neutron production cross section just above threshold energy.

A neutron source consists of an intimate mixture of target material and α-emitter. The α-particles are therefore slowed down in the source material and travel in all directions. Both these facts tend to smear out the structure in the neutron spectrum which would otherwise be found with thin targets. For α-particles of fixed energy E_α the relative number of neutrons produced within the source of energy between E_n and $E_n = dE_n$ is:[7]

$$F(E_n)\,dE_n = \frac{\sigma(\theta)}{\varepsilon}\,2\pi \sin\theta\,d\theta$$

The factor $1/\varepsilon$ expresses the probability of an α-particle having this energy E_α. The quantity ε is the stopping cross section at E_α in the source material. The neutron energy E_n in the laboratory system can be expressed as a function of the center-of-mass angle θ in the form[8] $E_n = a + b\cos\theta$. This allows rewriting of equation (1) in terms of E_n:

$$F(E_n)\,dE_n = \frac{\sigma(E_n)}{\varepsilon}\,4\pi\,\frac{dE_n}{E_n(\theta = 0°) - E_n(\theta = 180°)} \qquad (2)$$

The neutron energy distribution for this α-energy is therefore simply proportional to the differential cross section in the c.m. system when the latter is expressed as a function of neutron energy. This fact is illustrated in Fig. 2 where three of the distributions of Fig. 1 are redrawn in this manner. An isotropic angular distribution in the c.m. system results in a neutron spectrum of rectangular shape. By interpolation of these neutron energy distributions in steps of $\Delta E_\alpha = 10$ KeV, a family of spectra was obtained, which after summation results in the neutron source spectra of Fig. 3.

Table 1. *Neutron energy distribution*

Median energy (MeV)	Am-Li N_n	Po-Li N_n	Median energy (MeV)	Am-Li N_n	Po-Li N_n
0.02	128	170	0.78	266	259
0.06	318	422	0.82	253	242
0.10	462	588	0.86	240	226
0.14	526	582	0.90	227	210
0.18	517	562	0.94	215	194
0.22	500	542	0.98	203	178
0.26	480	519	1.02	190	160
0.30	461	496	1.06	176	142
0.34	442	474	1.10	161	121
0.38	425	453	1.14	145	100
0.42	407	432	1.18	129	78
0.46	390	412	1.22	113	56
0.50	374	392	1.26	97	34
0.54	357	372	1.30	81	12
0.58	341	353	1.34	65	0
0.62	326	333	1.38	49	0
0.66	310	314	1.42	34	0
0.70	295	295	1.46	17	0
0.74	280	277			
			$\Sigma N_n =$	10000	10000

Average energy and conversion d_k from fluence to kerma in wet tissue:
Am-Li: $\bar{E}_n = 0.535$ MeV, $d_k = (1.54 \pm 0.02) \times 10^{-7}$ erg g^{-1} cm^2.
Po-Li: $\bar{E}_n = 0.472$ MeV, $d_k = (1.44 \pm 0.02) \times 10^{-7}$ erg g^{-1} cm^2.

The calculation was carried out by using the stopping cross section ε for LiH since commercial sources are made using this source material. Except for the neutron yield the effect on the spectrum is negligible compared to a source containing elemental lithium. The heavy lines in Fig. 3 represent the most probable spectrum. The dotted and dashed spectra are obtained from angular distributions which are fitted to the endpoints of the error bars in Fig. 1. Since the neutron production cross section has not changed, the areas under the three curves are equal. From a peak at 110 keV for a Po-Li and 145 keV for an Am-Li source, both spectra show a smooth decrease to the maximum neutron energy. It is also seen in Fig. 3 that the neutron yield from an Am-LiH source is considerably higher than that of a Po-LiH source. A ratio of 1.33 was calculated.

To further illustrate the effect of the angular distribution, the dashed curve shows the Po-LiH source spectrum when an isotropic distribution in the c.m. system is assumed throughout the α-energy range. This spectrum contains more high energy neutrons since the low energy neutrons, caused by the backpeaking in the measured angular distribution, have been removed. The frequently quoted Po-Li source spectrum calculated by Hess[2] using an isotropic angular distribution is also shown. His spectrum is quite different from ours principally because Hess erroneously used a distribution proportional to sin θ instead of the rectangular neutron energy distribution produced by monoenergetic α-particles. Also, we have used new and more accurate neutron production cross sections. The spectrum from a Po-Li source had been measured before by Vialettes and LeThanh.[1] Between 0.18 and 1.3 MeV these authors were able to fit their data points to the spectrum of Hess. A ^{3}He proportional counter was used which required somewhat uncertain corrections for wall and end effects as well as for ^{3}He recoils.

Table 1 presents the calculated spectra in tabular form for 40 keV intervals to facilitate further manipulations. The average neutron energies are also given in this table, together with the fluence to kerma conversion for wet tissue, based on the kerma compilation published recently by the International Commission on Radiation Units and Measurements.[9]

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Comment on "A New Technique for Reactor Siting Dose Calculations"[1]

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This new technique of hazards evaluation recently proposed, is indeed an improvement over previously applied approaches.

The Gaussian representation of the concentration distribution of the released radioactivity has been chosen. It is the best and most convenient fit to experimental results though it differs from zero even at great distances from it's maximum while the concentration obviously does not. In view of the absence of a complete solution of this problem, one has to be very careful in cutting the zone of integration for direct γ dose computation.

The notations appearing in Willis *et al.* will be used hereafter. Assuming $Y_d = Y_1$, for instance, the part of the dose delivered by the radioactivity which is outside the 3σ region and near the detector, is not negligible. This is true especially at great distances downwind. A limit in the integration zone must therefore take into account the detector position as well as the mean free path.

Taking, for instance, Pasquill's stability category C, $X_d = 2000$ m, then $\Sigma = 200$ m. In this case

$$X_1 = X_d - 4_d\sigma_y = 1200 \text{ m}$$

$$X_2 = X_d + 4_d\sigma_y = 2800 \text{ m}$$